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DISTRIBUTION OF SOUND INTENSITY LEVEL OF FREQUENCY RESPONSES OF A ROOM

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In a number of investigations on the quantitative evaluation of the behaviour of the frequency response of a room, it has been assumed that above some boundary frequency this behaviour can be regarded as the result of a random process of summing up of reflected waves with an intensity level distribution close to a normal one. In the literature there is however lack of papers which confirm experimentally the correctness of this assumption or indicate its possible deviations from practical conditions. In view of this, investigations were undertaken to determine the form of the function of distribution of sound intensity level changes for a number of frequency responses registered in a few selected rooms (models) with varying acoustic properties. The investigation results obtained show that the functions of distribution of intensity level changes for these responses do sometimes differ a great deal from the normal one. This testifies that over the range of model investigations for which all the required conditions are satisfied, the assumption of a normal (Gaussian) distribution of the energy of reflected waves is not fulfilled.

1. Introduction

The purpose of the first papers [14, 1] on analysis of the behaviour of the frequency response of a room was mainly to determine for it such parameters as would describe quantitatively the irregularity of its behaviour. In these papers the frequency irregularity F of this response and the mean distance of its intensity level maxima were recognized to be the most essential parameters. A particularly detailed analysis of the behaviour of the frequency response was carried out in papers [9, 12], where new parameters were proposed for describing the behaviour of its irregularity and, as a result of theoretical considerations, some relationships between the mean distance of maxima of this response and the reverberation time of the room were derived. The properties of the frequency response were also considered from the point of view of correlation analysis [10]. The behaviour of the so-called frequency correlation functions obtained in this range for these responses permitted the determination, with given reverberation conditions in the room, of the frequency range beyond which values of the frequency response are not correlated with each other. Interesting results of investigations on the behaviour of the frequency response were given by the most recent papers on the subject [6, 5, 3], in which a functional relationship was shown to exist between the standard deviation, determined for this response, and the value of the critical distance of the room. As a result, it was possible to develop a new method for determining this distance.

It is interesting to note that in a number of the papers mentioned above it is assumed a priori that over some boundary frequency, the behaviour of the frequency response of the room can be regarded as the result of a random process of summing up of reflected waves with an intensity level distribution close to a normal one. This approach to the frequency response permitted the authors of these papers to carry out an analytical description of its definite parameters using statistical methods [9, 11]. It should be noted, however, that in the literature there is lack of papers confirming experimentally the correctness of this assumption or indicating its possible deviations from practical conditions. The strictness of this assumption thus requires experimental verification, the more so when it is considered that the room itself is a complex physical system whose character is to a varying degree determinate and in which the random nature of phenomena, in strictly probabilistic terms, requires deeper justification and analysis. This point of view warrants a supposition that probability distribution functions characterizing the random nature of these phenomena, will depend in a specific manner on some physical and geometrical quantities, such as: the reverberation time of the room, the distance between the source and the receiver, the directionality of the source etc. Keeping this in mind, research was undertaken with the essential aim of determining the form of sound intensity level distribution functions for a number of frequency responses recorded in some chosen rooms and defining some of its statistical parameters for these functions.

2. Irregularity of the behaviour of the frequency response of the room

The frequency response of a room is expressed in general by the irregularity of the transmission by the room of the intensity of a sinusoidal signal with its frequency changing with given rate. This irregularity is most often represented by the parameter F [1], which defines the difference between the extreme sums (i.e. the maximum sums $L_{\max}$ and the minimum ones $L_{\min}$) of sound intensity levels of this response, measured in the consecutive frequency bands Δf:

$$F = \frac{\sum L_{\max} - \sum L_{\min}}{\Delta f}. \tag{1}$$

It should be noted that the value of the parameter F, defined by formula (1), depends only on the resultant (summary) dynamics of extrema which fall in the range Δf and does not take into account their number, which often causes some ambiguities. For example, when considering two behaviours of the frequency response which differ considerably from each other, with one characterized by a small number of maxima but their high dynamics, the other in turn having a large number of maxima but their low dynamics, it is possible to obtain for these behaviours in some cases similar values of F.

The results of investigations carried out by SCHROEDER [9, 11, 12] indicate that there exists a relationship between the parameter F of the frequency response and the reverberation time T of a room. This relationship, as expressed by formula (2), is valid for frequencies f lying over some boundary frequency f_b, defined by expression (3),

$$F_s \simeq 1.4\,\mathrm{T}, \tag{2}$$

where F_s – irregularity of the frequency response (acc. to SCHROEDER),

$$f \geqslant f_b = 4000\sqrt{T/V}, \tag{3}$$

where V – the volume of the room.

It follows from formula (2) that irregularity of the frequency response of a room is proportional to its reverberation time. Apart from studies of the irregularity of the frequency response of a room, research work was also carried out on the irregularity of the distribution of its maxima on the frequency scale. In their experimental papers, KUTTRUFF and THIELE [7] showed that the average spacing δf between adjacent maxima of the frequency response was inversely proportional to the reverberation time of the room.

$$\delta f \simeq \frac{6.7}{T}. \tag{4}$$

However, according to the later theoretical and experimental research [12], the average spacing between adjacent maxima of this response is less than that given by formula (4), being

$$\delta f \simeq \frac{3.9}{T}. \tag{5}$$

It should be added that the experimentally determined value of δf depends to a large extent on the parameters of the measuring system. E.g. according to paper [12], in determining the quantity δf sometimes results are obtained, which differ from each other by as much as about $50^0/_0$, depending on the quantization properties of the recorder used for registering the frequency response.

The behaviour of the frequency response of a room is usually considered, for frequencies above some boundary value, as a result of statistical phenomena, based on the assumption of a random character of summing up of a direct wave and a large number of reflected waves, with different amplitudes and phases. This signifies that in describing the irregularity of the behaviour of this response, also other, more strictly defined mathematically than the quantity F, statistical parameters can be introduced, such as the mean square fluctuation of the frequency response and probability moments of higher order. Statistical treatment of this response as some random process with distribution close to a normal one provided the basis for investigations of its so-called frequency correlation function [10], according to which an analytical expression of this function has the form

$$\varrho(\delta f') = \frac{1}{4-\pi}\left[2(1+z)f\left(\frac{2\sqrt{z}}{1+z}\right)-\pi\right], \tag{6}$$

where $\delta f'$ — frequency interval (analogous to the time interval δt of the autocorrelation function $\varrho(\delta t)$), $z = [1+(2\pi\tau\delta f')]^{-1/2}$, $\tau = T/13.8$, $f(...)$ — hypergeometrical function.

Analysis of the behaviour of the frequency autocorrelation function indicates that it shows a distinct tendency to decrease with increasing $\delta f'$, reaching a value of the order of 0.1 for the frequency interval $\delta f' = 6.6/T$. On this basis, it can be assumed that at frequency intervals, of $6/T$ approximately [Hz], values of the maxima of the frequency response of a room are independent of each other.

The assumption of a random sound pressure amplitude distribution in the room encouraged us to seek an analytical form of the probability density function of this distribution.

According to papers [12, 4], when a room is excited by signals with frequencies above some boundary value f_b, the probability density function of the sound pressure amplitude distribution at some distance from the source has the form

$$Pr(p) = \frac{2p}{\langle p_r^2\rangle}\exp\left(-\frac{p^2+p_d^2}{\langle p_r^2\rangle}\right)J_0\left(\frac{2pp_d}{\langle p_r^2\rangle}\right), \tag{7}$$

where p — the resultant sound pressure, composed of the sound pressure of the direct wave p_d, which is a deterministic component, and the sound pressure of the reflected waves $\langle p_r\rangle$, which is a random component; J_0 — a Bessel function of the first kind of the zeroth order; $\langle\rangle$ — averaging over the set of reflected waves.

Using the dependence $I \sim p^2$, the density function of the sound pressure amplitude distribution, $Pr(p)$, can be expressed as a function of the density distribution of its intensity $Pr(I)$,

$$Pr(I) = \frac{1}{\langle I_r \rangle} \exp\left(-\frac{I+I_d}{\langle I_r \rangle}\right) J_0\left(\frac{2\sqrt{II_d}}{\langle I_r \rangle}\right), \quad (8)$$

where $I = I_d + I_r$ – the resultant sound intensity at a given measurement point.

Designating as D the ratio of the direct sound intensity I_d to the reflected (reverberant) sound intensity I_r, i.e.

$$D = \frac{I_d}{\langle I_r \rangle}, \quad (9)$$

and replacing intensity by its logarithmic measure, i.e. the intensity level L,

$$L = 10\log\frac{I}{\langle I \rangle} \quad [\text{dB}], \quad (10)$$

we obtain the expression of the probability density function of the sound intensity level distribution, depending on the parameter D, in the form

$$Pr(L) = k(1+D)\exp\{-[(1+D)\exp(kL)+D]+kL\}J_0\{2\sqrt{[(1+D)D\exp(kL)]}\}, \quad (11)$$

where $k = \ln 10/10 = 0.23$.

On the assumption that $D \to 0$, i.e. with $I_d \to 0$ (at a large distance from the source), the density function represented by expression (11) becomes (12):

$$Pr(L) = k\exp\big(kL - \exp(kL)\big) = 0.23\exp\big(0.23L - \exp(0.23L)\big). \quad (12)$$

It is interesting to add that for a definite distance in a source-microphone system the behaviour of frequency responses, recorded for changing the position of the system in a room, will be different from each other, sometimes quite considerably so; however, the statistical properties of these responses will be independent of this position (under the condition that the source-microphone system is not situated close to the surfaces enclosing the room). In turn, a change in the distance between the source and the microphone causes a change both in the behaviour of the frequency response and the value of the parameter D. This fact does not undermine, however, the validity of expression (11), which still describes the form of the probability density function of the distribution of these responses.

Knowledge of the probability density function of the intensity level, $Pr(L)$, of the frequency response of a room can permit the moments M of appropriate orders to be determined for it, according to formula (13),

$$\langle L^M \rangle = \int_{\infty}^{\infty} L^M Pr(L)\, dL. \quad (13)$$

For $M = 1$ the mean value of this function can be obtained,

$$\langle L \rangle = \int_{-\infty}^{\infty} L Pr(L) dL, \tag{14}$$

whereas for $M = 2$ the mean square value

$$\langle L^2 \rangle = \int_{-\infty}^{\infty} L^2 Pr(L) dL. \tag{15}$$

can be determined.

From this, the value of the standard deviation σ of the function $Pr(L)$ can be found, from formula (16),

$$\sigma(D) = \sqrt{\langle L^2 \rangle - \langle L \rangle^2} = \sqrt{\int_{-\infty}^{\infty} L^2 Pr(L) dL - [\int_{-\infty}^{\infty} L Pr(L) dL]^2}. \tag{16}$$

Fig. 1. shows a curve of the dependence of the standard deviation σ on the logarithmic value of the ratio of the direct sound intensity to the reverberant sound intensity [5]. It is seen in this picture that the measurement of the standard deviation of the frequency response permits the critical dis-

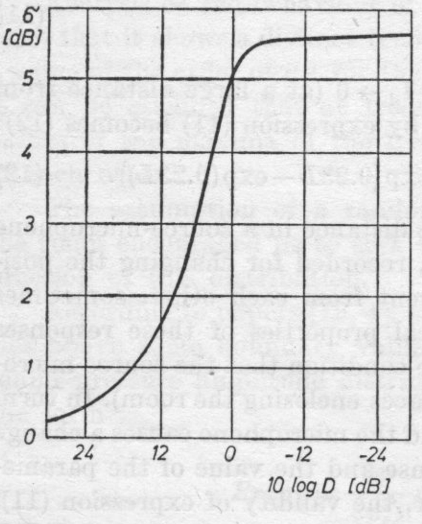

Fig. 1. The dependence of the standard deviation σ of the frequency response of a room on the value $10 \log D = 10 \log I_d/I_r$ [s]

tance of the room to be determined, i.e. the distance at which the quantity $D = I_d/\langle I_r \rangle$ is 1. This problem was considered in greater detail in papers [6, 5, 3]. It is also seen in this figure that in the reverberant field the standard deviation of the frequency response has a constant value of about 5.6 dB. It should be noted that the method proposed above for determining the critical distance from the measurement of the standard deviation of the frequency response assumes lack of directionality of the source and receiver. In practice, however, these transducers always involve some directional effect, and accordingly, in determining exact values of this distance, the value of their directionality coefficients should be taken into account.

It can be seen from the above considerations that the behaviour of the frequency response of a room is usually regarded as a result of random processes of a type for which the form of the probability density function is assumed to be close to the density function of a normal distribution. This assumption had not been verified experimentally in previous investigations, neither for actual rooms, nor in model studies. Moreover, the possible deviations of the form of this function for practical distributions from those assumed in theoretical considerations are also unknown. This fact encouraged us to undertake investigations with the main aim of experimental verification of this assumption. This verification was carried out on the basis of analysis of the form of histograms of sound intensity level distribution, as determined for a number of frequency responses recorded in a few acoustically different model rooms which satisfied the condition $l \gg \lambda$. In addition, within the framework of the present investigations, the values of basic statistical parameters were also determined for these histograms.

3. Measurement object, investigation apparatus and method

The investigations were carried out in a special (model) room, in which four forms of interior with different acoustical properties could be shaped, designated below as rooms: B (damped), C (undamped), and D and E, which were acoustically coupled rooms, with different values of the coupling coefficient Q [8]. In rooms B and C measurement points were chosen; their situation is shown in Fig. 2. In addition this figure also shows the distribution

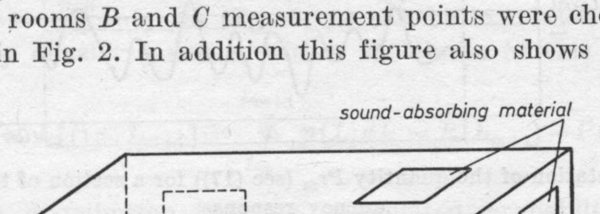

Fig. 2. The position of the measurement points P_1 ($x = 5$, $y = 0$, $z = 0$), P_2 ($x = 100$, $y = 0$, $z = 0$), P_3 ($x = 112$, $y = 20$, $z = 32$), P_4 ($x = 135$, $y = 30$, $z = 60$) and the distribution of absorbing materials in room B

of the absorbing material, with a mean absorption coefficient $\alpha \simeq 0.6$ over the frequency range 630–4000 Hz, with which room B was damped.

A schematic diagram of the measurement apparatus system, in which an essential role was played by a statistical distribution analyser, connected to a unit of digital signal processing, is shown in Fig. 3.

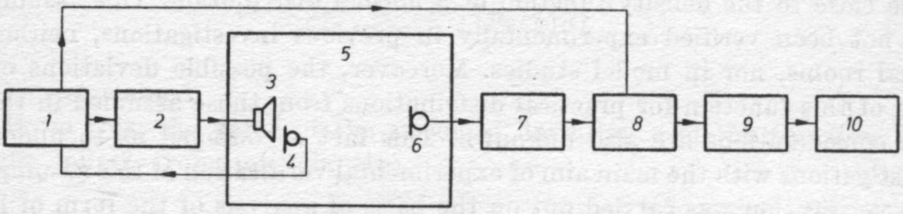

Fig. 3. A schematic diagram of the apparatus used for measuring the frequency response of a room

1 – generator, *2* – power amplifier, *3* – loudspeaker type 400 G, diameter 2 cm, *4* – compensation microphone (nondirectional, *B*–K), *5* – room investigated, *6* – measurement microphone nondirectional, B–K), *7* – microphone amplifier, *8* – plotter voltmeter, *9* – statistical distribution analyser, *10* – computer

Fig. 4 illustrates the essence of analysis of the behaviour of the frequency response. The intensity level $L(f)$, variable as a function of frequency, is divided

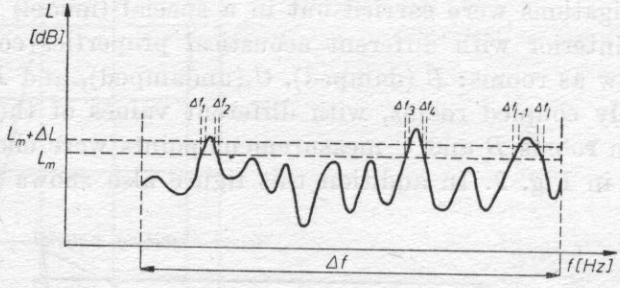

Fig. 4. An interpretation of the quantity Pr_m (see (17)) for a section of the curve of the frequency response

into adequate intervals (classes), contained within the limits from L_m to $L_m + \Delta L$, where ΔL is a constant level increase, and $m = 1, 2, \ldots, r$. The probability that the level $L(f)$ falls in some interval $(L_m, L_m + \Delta L)$ can be represented in the following way:

$$Pr_m[L_m \leqslant L(f) \leqslant L_m + \Delta L] = \frac{\sum_{i=1}^{l} \Delta f_i}{\Delta f}. \tag{17}$$

This magnitude of the probability Pr_m for successive intervals of the intensity level can be determined from indications of the statistical distribution analyser. The values of Pr_m falling in particular intervals can be represented graphically by a histogram (see Fig. 5), which illustrates the probability distribution of sound intensity level changes over a given bandwidth Δf of the frequency response. Passing within the limits from ΔL to zero, we can obtain the

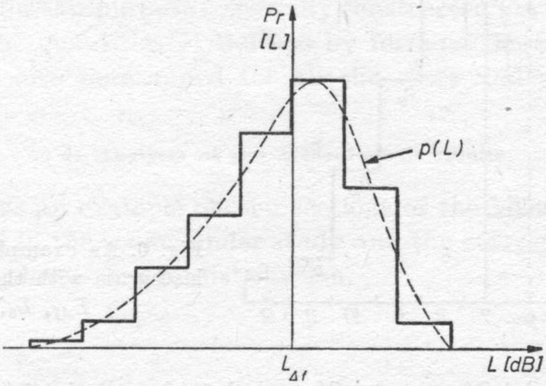

Fig. 5. An example of the histogram of the probability distribution of sound intensity level changes for the frequency response of a room

form of the probability density function $p(L)$, marked by dashed line in Fig. 5,

$$p(L) = \lim_{\Delta L \to 0} \frac{Pr_m [L_m \leqslant L(f) \leqslant L_m + \Delta L}{\Delta L}. \tag{18}$$

With this boundary condition, the probability that the function $L(f)$ takes a value from any interval (L_m, L_{m+1}) can be expressed by an integral of the probability density function within the limits of this interval, i.e.

$$Pr[L_m \leqslant L(f) \leqslant L_{m+1}] = \int_{L_m}^{L_{m+1}} p(L)\,dL = P(L_{m+1}) - P(L_m), \tag{19}$$

where $P(L)$ is a distribution function (cumulated probability distribution function).

The statistical distribution analyser used in the investigations permitted values of Pr_m to be determined in successive intervals of sound intensity level, each 5 dB wide (which resulted from the dynamics range of the potentiometer used). These values permitted in turn histograms of the probability distribution of intensity level changes (see Figs. 9 and 12) to be plotted for a large number of different frequency responses recorded at chosen measurement points of the room under study.

In addition, from indications of the statistical distribution analyser, the mean values of the intensity level $L_{\Delta f}$ and the standard deviation $\sigma_{\Delta f}$ from $L_{\Delta f}$ were also calculated from formulae (20) and (21) [2].

The symbols used in these formulae are defined, as an example, in the histogram given in Fig. 6.

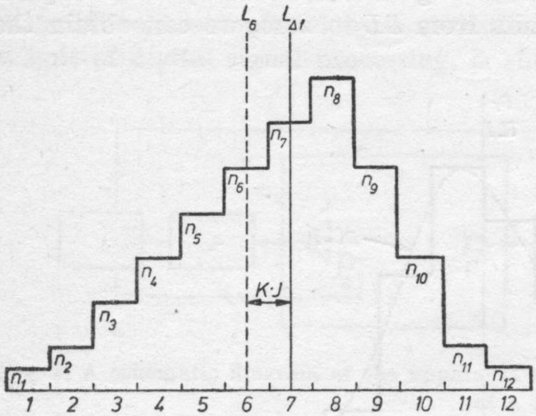

Fig. 6. An example of the distribution histogram with the marked quantities $L_{\Delta f}$, L_6, $n_1, \ldots, n_{12}$

$$K = \frac{1}{N}[(n_7-n_5)+2(n_8-n_4)+3(n_9-n_3)+4(n_{10}-n_2)+5(n_{11}-n_1)+6n_{12}];$$

$$L_{\Delta f} = L_6+KJ = L_6+K5 \quad [\mathrm{dB}]; \tag{20}$$

$$R = \sqrt{\frac{1}{N}[(n_7+n_5)+4(n_8+n_4)+9(n_9+n_3)+16(n_{10}+n_{12})+25(n_{11}+n_1)+36n_{12}]-K^2};$$

$$\sigma_{\Delta f} = RJ = R5 \quad [\mathrm{dB}], \tag{21}$$

where $N = n_1+n_2+\ldots+n_{12}$ – the summary number of countings of the statistical analyser over a given frequency band Δf (the particular bands Δf, into which the frequency response of the room was divided, corresponded to 1/3 octave bandwiths); $n_1, n_2, \ldots, n_{12}$ – the number of countings in successive channels of the statistical analyser for a given band Δf; L_6 – the value of intensity level corresponding to channel 6 of the statistical analyser, J – channel unit equal to 1/10 of the value of the dynamics of the potentiometer used (in the present case $J = 5$ dB), $L_{\Delta f}$ – the mean value of sound intensity level of the frequency response, determined in the band Δf; $\sigma_{\Delta f}$ – the standard deviation of the frequency response from its mean value $L_{\Delta f}$, determined in the band Δf.

In order to evaluate qualitatively the degree of deviation of histograms obtained from a histogram corresponding to a normal distribution, values of the asymmetry coefficient A, defined by formula (22), were determined for them,

$$A = \frac{E[(L-L_{\Delta f})^3]}{\sigma^3} = \frac{\mu_3}{\sigma_3}, \tag{22}$$

where $E[]$ — the symbol of the mathematical expectation, μ_3 — the moment of the third order with respect to the mean value $L_{\Delta f}$.

For a symmetrical histogram form (i.e. for a normal distribution), this coefficient takes a zero value.

Values of the parameters $L_{\Delta f}$, $\sigma_{\Delta f}$ and A were determined by numerical calculations using for this purpose a specially constructed Fortran IV programme [8]. In addition the quantities F, defined by formula (1), and F_s, defined by formula (2), were also determined for all the cases under study.

4. Analysis of the measurement results

Fig. 7 shows as an example chosen sections of the behaviour of frequency responses recorded in the rooms under study and the corresponding histograms of sound intensity level change distribution.

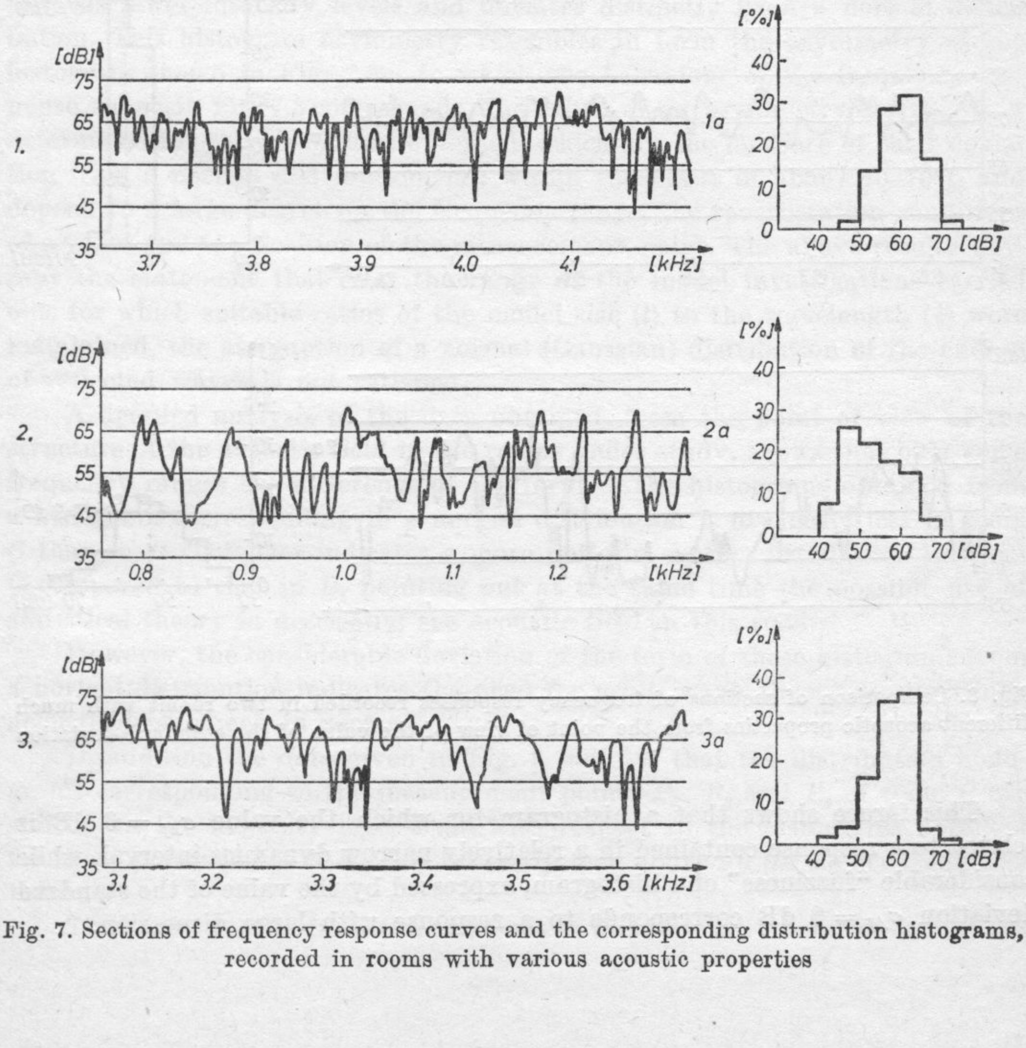

Fig. 7. Sections of frequency response curves and the corresponding distribution histograms, recorded in rooms with various acoustic properties

It is seen in Fig. 7 that these histograms are related in an interesting way to the character of the behaviour of the frequency response of the room. Thus, in a case when the behaviour of this response is close to the random behaviour (Fig. 7.1), the corresponding histogram takes a form corresponding in approximation to a normal distribution (Fig. 7.1*a*). The histogram shown in Fig. 7.2*a* corresponds to the behaviour of the response with maxima distinct on the amplitude scale (Fig. 7.2), while the histogram in the form shown in Fig. 7.3*a* is related to the response with clearly distinct minima (Fig. 7.3).

In addition it should be noted that the form of a distribution histogram also gives interesting information on the magnitude of dispersion of the frequency response of a room, whose measure is the value of the mean standard deviation, graphically illustrated in Fig. 8.

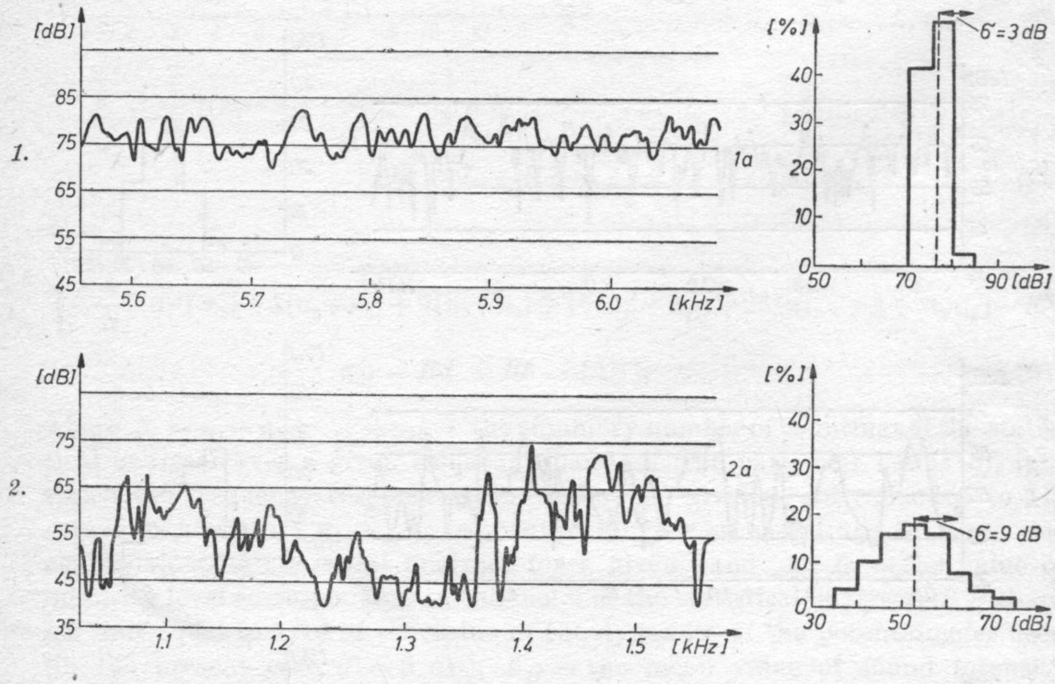

Fig. 8. Comparison of sections of frequency responses recorded in two rooms with much different acoustic properties from the point of view of the value of the standard deviation

This figure shows that a histogram for which the value $\sigma_{\Delta f} = 3$ dB is related to a response contained in a relatively narrow dynamics interval, while considerable "fuzziness" of a histogram, expressed by the value of the standard deviation $\sigma_{\Delta f} = 9$ dB corresponds to a response with large dispersion.

In order to analyse the form of the probability density function for the frequency responses under study, recorded in the rooms mentioned above, histograms of intensity level change probability distribution in successive 1/3 octave bands (Δf), within the range 630–8000 Hz, were plotted for these responses and the mean values of these levels ($L_{\Delta f}$) and the standard deviation ($\sigma_{\Delta f}$) calculated. The relatively high range of the frequencies considered resulted from the fact that the model investigations carried out required that a suitable ratio of the wavelength to the model size should be maintained. Some of these histograms, obtained for the considered measurement points of the damped room B (—) and the undamped room C (– – –), are shown as an example in Fig. 9.

From analysis of the form of the histograms shown in Fig. 9, it can be stated in general that the probability distribution of sound intensity level changes in the frequency response of a room indicates considerably asymmetry towards lower intensity levels and deviates distinctly from a normal distribution. This histogram asymmetry resembles in form the asymmetry of the histogram shown in Fig. 7.3*a*, to which the behaviour of the frequency response shown in Fig. 7.3 corresponds. The values of the asymmetry coefficient A determined for the histograms obtained, which are the measure of their deviation from a normal distribution, fall within the limits of about 40–70°/₀ and depend to a large degree on the frequency range, the reverberation conditions of a room and the position of the measurement point. The above results warrant the statement that over the range of the model investigations carried out, for which suitable ratios of the model size (l) to the wavelength (λ) were maintained, the assumption of a normal (Gaussian) distribution of the energy of reflected waves is not satisfied.

A detailed analysis of the data obtained, from the point of view of the structure of the acoustic field in the rooms under study, shows that over some frequency ranges the difference of the form of the histograms obtained from a histogram corresponding to a normal distribution is distinctly less in room C than in B. This fact indicates a more uniform energy distribution in room C compared to that in B, pointing out at the same time the possible use of statistical theory in describing the acoustic field in this room.

However, the considerable deviation of the form of these histograms from a normal distribution indicates the need for using wave theory in describing acoustic phenomena in rooms.

In addition the data given in Fig. 9 indicate that the distribution histograms corresponding to the measurement points P_2, P_3 and P_4 of room C are shifted on the intensity level scale with respect to the histograms obtained for those points in room B. This is clearly seen above all for higher frequency bands.

This effect results from the existence of different reverberation conditions

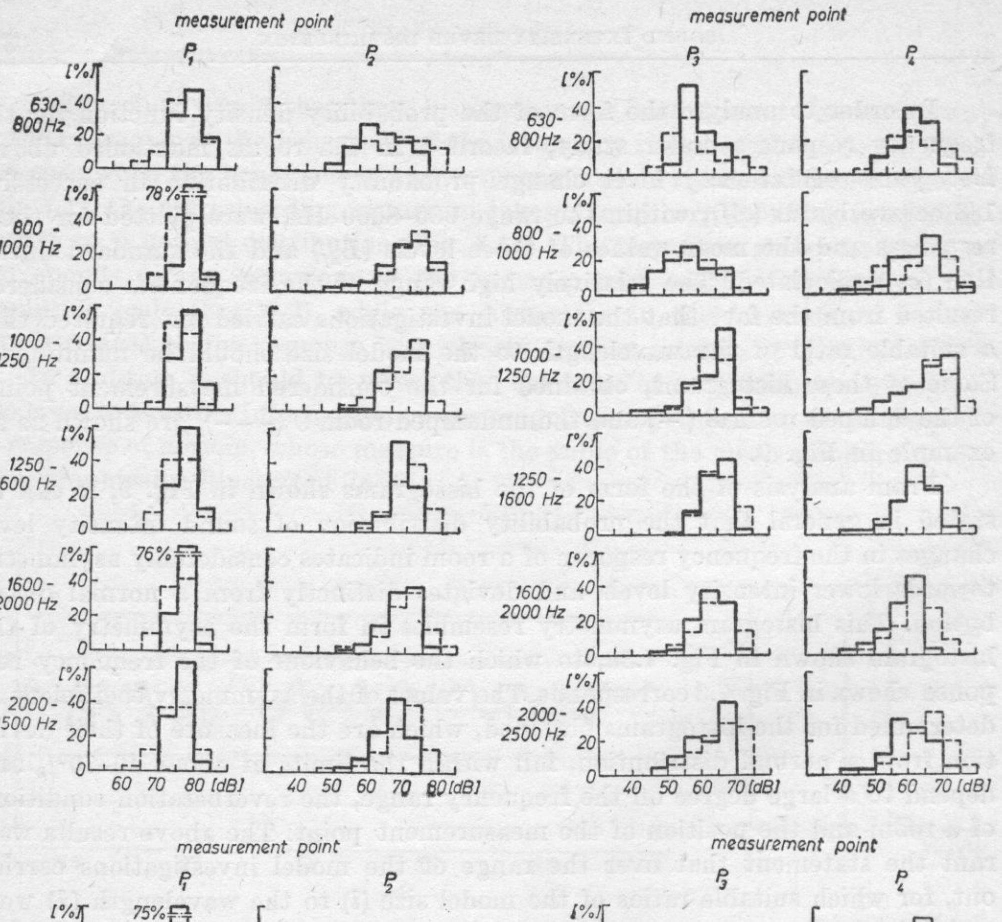

Fig. 9. Histograms of sound intensity level change distribution of frequency responses for successive 1/3 octave bands, measured at the measurement points P_1, P_2, P_3 and P_4 in room B (———) and room C (– – –)

in these rooms, on which the resultant value of sound intensity level is known to depend.

Comparison of the histograms obtained in the rooms under study, from the point of view of their "fuzziness", whose measure is the value of the standard deviation, indicates that the histograms for room C are more "fuzzy" than those for room B. In addition the change in the outline of these histograms, which is interesting with changes in the acoustical properties of the room, for some frequency bands and some measurement points represents a definite change in the distribution of maxima and minima of the frequency responses of the room, as was already mentioned in discussing Fig. 7.

Comparison of the mean values of the level $L_{\Delta f}$ of the frequency responses of rooms B and C in successive 1/3 octave bands is shown jointly in Fig. 10, line 1, whereas the values of the standard deviation $\sigma_{\Delta f}$ corresponding to these responses and determined in these bands are given in line 2. In addition the so-called irregularity density F[1], whose behaviour is shown in Fig. 10, line 3, was also calculated for these responses.

The mean values of the reverberation time T and the parameters $L_{\Delta f}$, $\sigma_{\Delta f}$, F and F_s, measured in rooms B and C at the measurement points P_1, P_2, P_3 and P_4, are given jointly in Table I.

In addition to investigations carried out in parallel-piped rooms B and C, analogous measurements were also carried out in two coupled rooms D and E, which differ from each other with the value of the coupling coefficients Q_{I} and Q_{II}, defined as

$$Q_{\mathrm{I}} = \frac{S_0}{a_{\mathrm{I}} S_{\mathrm{I}} + S_0}; \tag{23}$$

$$Q_{\mathrm{II}} = \frac{S_0}{a_{\mathrm{II}} S_{\mathrm{II}} + S_0}; \tag{24}$$

where Q_{I} – the coefficient of coupling the volume V_{I} with the volume V_{II}; Q_{II} – the coefficient of coupling the volume V_{II} with the volume V_{I}; a_{I}, a_{II} – the absorption coefficients of the volumes V_{I} and V_{II}; S_{I}, S_{II} – the surface areas of the walls of the volumes V_{I} and V_{II}: S_0 – the surface area of the coupling opening.

In the case of the coupled room D, part of the surface enclosing the volume V_{I} was covered with absorbing material (see Fig. 11), thus achieving, despite the different volumes V_{I} and V_{II}, close values of the acoustic coupling coefficients Q_{I} and Q_{II}, respectively: $Q_{\mathrm{I}} = 0.22$; $Q_{\mathrm{II}} = 0.24$. In turn, in the case of room E the surfaces enclosing the volumes V_{I} and V_{II} were made of the

[1] The author distinguishes between the so-called irregularity density of the frequency response, expressed by formula (1) and designated as F [dB/Hz], and the notion of dispersion of this response, whose measure is the quantity $\sigma_{\Delta f}$ [dB], expressed by formula (21).

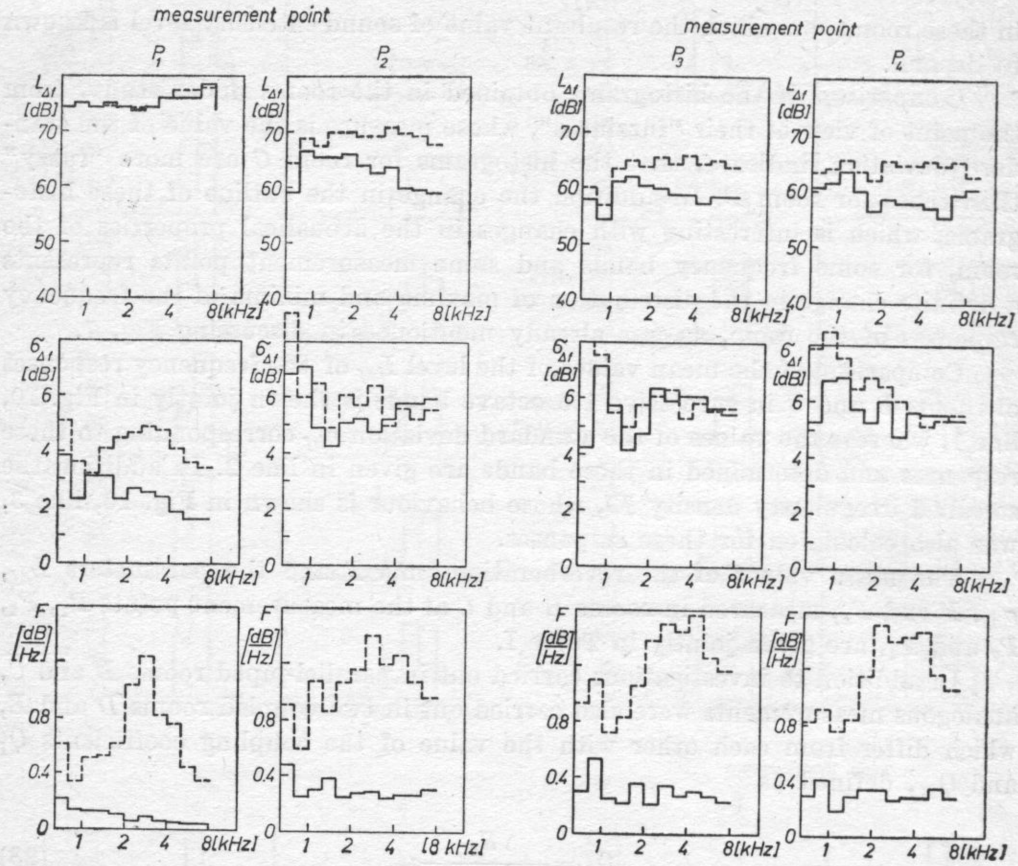

Fig. 10. Behaviour of the mean values of the intensity level $L_{\Delta f}$, the standard deviation $\sigma_{\Delta f}$ and the irregularity density F, determined for successive 1/3 octave bands of frequency responses, as recorded at the points P_1, P_2, P_3 and P_4 in room B (———) and room C (— — —)

same material with the mean absorption coefficient $a \simeq 0.05$, effecting as a result a double increase in the coupling coefficient of the volume $V_{\rm I}(Q_{\rm I} = 0.47)$ compared with the coupling coefficient of the volume $V_{\rm II}$ $(Q_{\rm II} = 0.24)$.

The distribution of the absorbing materials and the position of measurement points in the coupled rooms are shown in Fig. 11. Fig. 12 shows as an example a comparison of sound intensity level distribution histograms for sucessive 1/3 octave bands of frequency responses obtained at the points $P_{2.\rm I}$ and $P_{2.\rm II}$, which fall in the volumes $V_{\rm I}$ and $V_{\rm II}$ of the coupled rooms D and E. These data show that the distribution histograms for the coupled room D are displaced on the level scale with respect to the histograms obtained for room E. This displacement clearly depends on the frequency band considered, with, both for the measurement point $P_{2.\rm I}$ and $P_{2.\rm II}$, above 2000 Hz, histograms for room E being displaced towards higher levels.

On the basis of the asymmetry coefficients determined for these histo-

Table I. The mean values of the reverberation time T and the parameters $L_{\Delta f}$, $\sigma_{\Delta f}$, F and F_s, obtained in rooms B and C, at the measurement points P_1, P_2, P_3 and P_4 (with averaging carried out over the frequency range 630–8000 Hz)

Measurement point	Room R (damped)					Room C (undamped)				
	T	$L_{\Delta f}$	$\sigma_{\Delta f}$	F	F_s	T	$L_{\Delta f}$	$\sigma_{\Delta f}$	F	F_s
	[s]	[dB]	[dB]	[dB/Hz]	[dB/Hz]	[s]	[dB]	[dB/Hz]	[dB/Hz]	[dB/Hz]
P_1 ($x = 5, y = 0, z = 0$)	—	75	2.6	0.08	—	—	75	4	0.65	—
P_2 ($x = 100, y = 0, z = 0$)	0.2	61	5.6	0.28	0.25	0.7	67	6	0.95	0.98
P_3 ($x = 112, y = 20, z = 32$)	0.22	58	5.6	0.3	0.3	0.75	62	5.8	1.05	1.05
P_4 ($x = 135, y = 30, z = -60$)	0.22	58	5.6	0.3	0.3	0.75	63	6.0	1.02	1.05

Table II. The mean values of the reverberation time T and the parameters $L_{\Delta f}$, $\sigma_{\Delta f}$, F and F_s, obtained in the coupled rooms D and E, at the measurement points $P_{2.\mathrm{I}}$ and $P_{2.\mathrm{II}}$ (with averaging carried out over the frequency range 630–8000 Hz)

Measurement point	Coupled room D					Coupled room E				
	T	$L_{\Delta f}$	$\sigma_{\Delta f}$	F	F_s	T	$L_{\Delta f}$	$\sigma_{\Delta f}$	F	F_s
	[s]	[dB]	[dB]	[dB/Hz]	[dB/Hz]	[s]	[dB]	[dB]	[dB/Hz]	[dB/Hz]
$P_{2.\mathrm{I}}$($x = 38, y = 20, z = 32$)	0.35	57	6.5	0.20	0.49	0.6	63	5.7	0.57	0.84
$P_{2.\mathrm{II}}$($x = 100, y = 0, z = 0$)	0.55	56	5.8	0.58	0.77	0.7	63	5.7	0.68	0.98

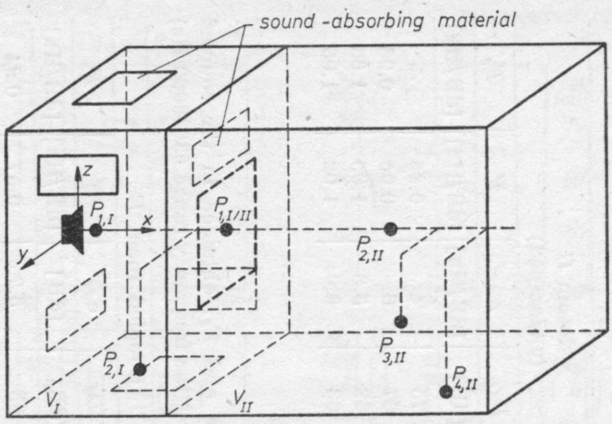

Fig. 11. The distribution of absorbing materials and the position of the measurement points $P_{2.\mathrm{I}}$ ($x = 38$, $y = 20$, $z = 32$) and $P_{2.\mathrm{II}}$($x = 100$, $y = 0$, $z = 0$) in the coupled room D

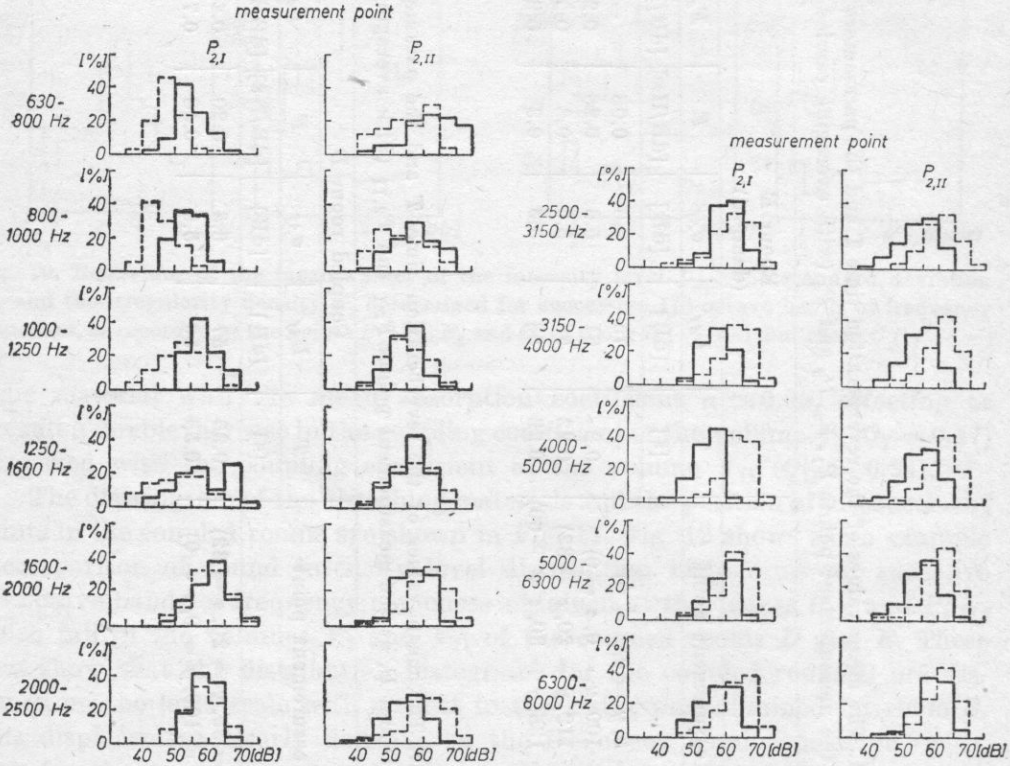

Fig. 12. Histograms of sound intensity level change distribution of frequency responses for successive 1/3 octave bands, measured at the measurement points $P_{2.\mathrm{I}}$ and $P_{2.\mathrm{II}}$ in the coupled rooms D (———) and E (– – –)

grams, it can be stated in general that, similarly to rooms B and C, in the coupled rooms the sound intensity level change distribution of the frequency responses analysed deviates from a normal one. Interesting information on the magnitude of dispersion of the frequency responses of rooms D and E is contained in the "fuzziness", various in form, of particular histograms. Comparison of the mean values of intensity level, $L_{\Delta f}$, for the frequency responses of the coupled rooms D and E the values of the standard deviation corresponding to these levels, and also values of the parameter F for successive 1/3 octave bands of these responses, are given in Fig. 13. In turn the mean values of the parameters $L_{\Delta f}$, $\sigma_{\Delta f}$ and F, measured at the points $P_{2.\mathrm{I}}$ and $P_{2.\mathrm{II}}$ of the coupled rooms D and E, are given jointly in Table II.

It is seen in Fig. 13 that in the volume V_{I} (measurement point $P_{2.\mathrm{I}}$ of the coupled rooms D and E) there is a quite large differentiation in the behaviour of the values of the parameters $L_{\Delta f}$ and F. In turn, in the volume V_{II} (measurement point $P_{2.\mathrm{II}}$), which is the same in terms of size and interior decoration for rooms D and E, the difference between the behaviour of the value of the coefficient $L_{\Delta f}$ for these rooms is still quite large, whereas the behaviours of the coefficient F in these rooms are quite close. The values of the standard deviation $\sigma_{\Delta f}$ for rooms D and E do not show unambiguous differences either in the volume V_{I} or in V_{II}, but they are different for these volumes in the character of the behaviour as a function of frequency.

In conclusion, it should be stressed that apart from the model investigations carried out, it is essential to verify experimentally the assumption of a random distribution of the energy of reflected waves in real rooms with large volume.

5. Conclusions

1. A detailed analysis of ample experimental material shows that histograms of sound intensity level change distribution of the analysed frequency responses obtained for the rooms under study are different from a normal distribution within the limits of the asymmetry coefficient up to as much as 70%. This difference depends to a large extent on the reverberation conditions of the room, the frequency band and the position of the measurement point. The results of the present experimental investigations thus permit the statement that in the range of model investigations the assumption of a normal (Gaussian) distribution of the energy of reflected waves is not satisfied.

2. The forms of histograms describing the sound intensity level distribution of frequency responses recorded at chosen measurement points and the corresponding values of the asymmetry coefficients A permit the establishment of a criterion for selecting an adequate (statistical or wave) theory for description of acoustic phenomena in a room. It can be assumed that the distribution histograms which are close to a normal distribution within the

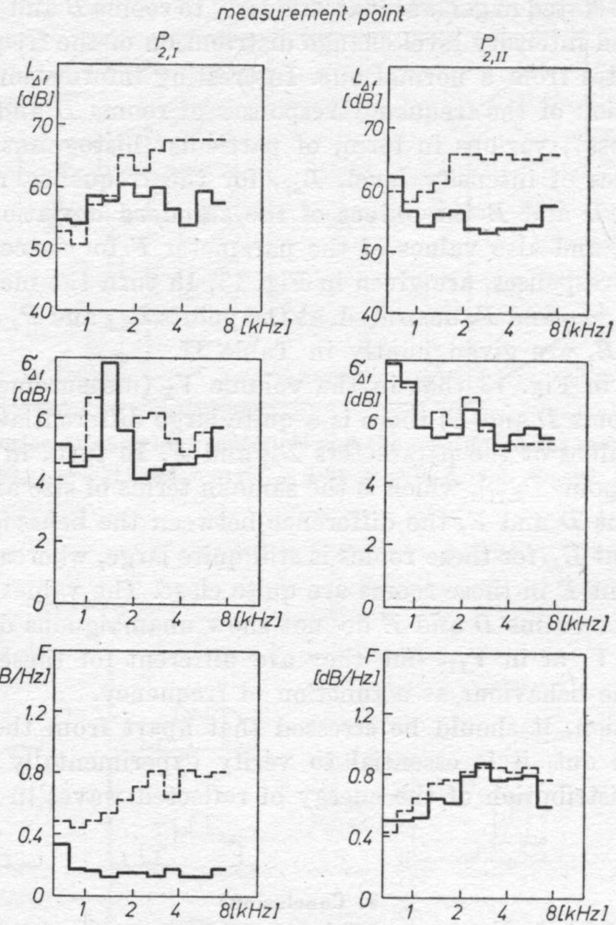

Fig. 13. Behaviour of the mean values of the intensity level $L_{\Delta f}$, the standard deviation $\sigma_{\Delta f}$ and the irregularity density F, as determined for successive 1/3 octave bands of frequency responses recorded at the points $P_{2.\mathrm{I}}$ and $P_{2.\mathrm{II}}$ in the coupled rooms D (———) and E (— — —).

limits of a small value of A represent well a uniform distribution of the energy of the acoustic field in a room, suggesting at the same time the possibility of describing the field by statistical theory. In turn the large deviation of the forms of these histograms from a normal distribution, which is expressed by a high value of A, suggests the need for analysis of acoustic phenomena in a room by means of wave theory.

3. The mean value of the standard deviation from the value $L_{\Delta f}$ for frequency responses, determined in the reverberant field of the rooms considered, falls within the limits 5.6–6 dB and is in good agreement with an analogous quantity defining the irregularity of the distribution of acoustic energy in a room, of about 5.6 dB, as obtained in paper [9]. It should be added that

this value corresponds to the mean change in the intensity level of the spectral components of the sound spectrum analysed in paper [8].

4. The results of measurements of the parameter F of frequency responses recorded in rooms B and C are in good agreement with those of calculations of the parameter F_s, determined from formula (2). However, in the coupled rooms D and E measurements of the parameter F give in all cases values much lower than those of F_s.

The investigation results given above and their analysis indicate that interesting information on the behaviour of the frequency response of a room can be gained by analysing its statistical parameters. It can be expected that, apart from the distribution histograms and the corresponding mean values, standard deviations and asymmetry coefficients, determined above for frequency responses under study, determination for these responses of other additional parameters, based on statistical moments of higher orders, would permit an even more accurate description of the behaviour of the frequency response, and thus a fuller evaluation of the structure of the acoustic field in a room.

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